

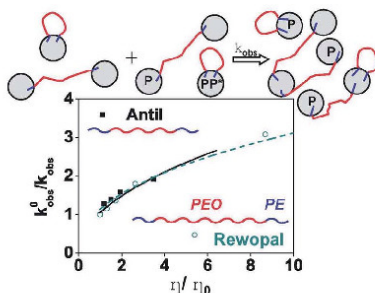


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# Dynamics of Solubilisation Processes in Amphiphilic Systems Studied by Highly Time-Resolved Stopped-Flow Experiments

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# 1 Introduction

In aqueous solution many surfactants exhibit a rich phase behavior due to their ability to self-assemble into a large variety of morphologically different structures. The simplest ones are micellar structures of e.g. spherical or cylindrical shape to more complex ones like lamellar, vesicle or sponge phases.

Originally proposed by Tanford [1] but later refined, Israelachvili et al. [2] introduced the concept of the so-called packing parameter in 1976, a theoretical framework that relates molecular parameters (head group area, chain length, hydrophobic tail volume) and intensive variables (temperature, ionic strength etc.) to surfactant microstructures and which provides the opportunity to 'tailor' the amphiphilic morphology as desired.

The (critical) packing parameter  $P$  is given by

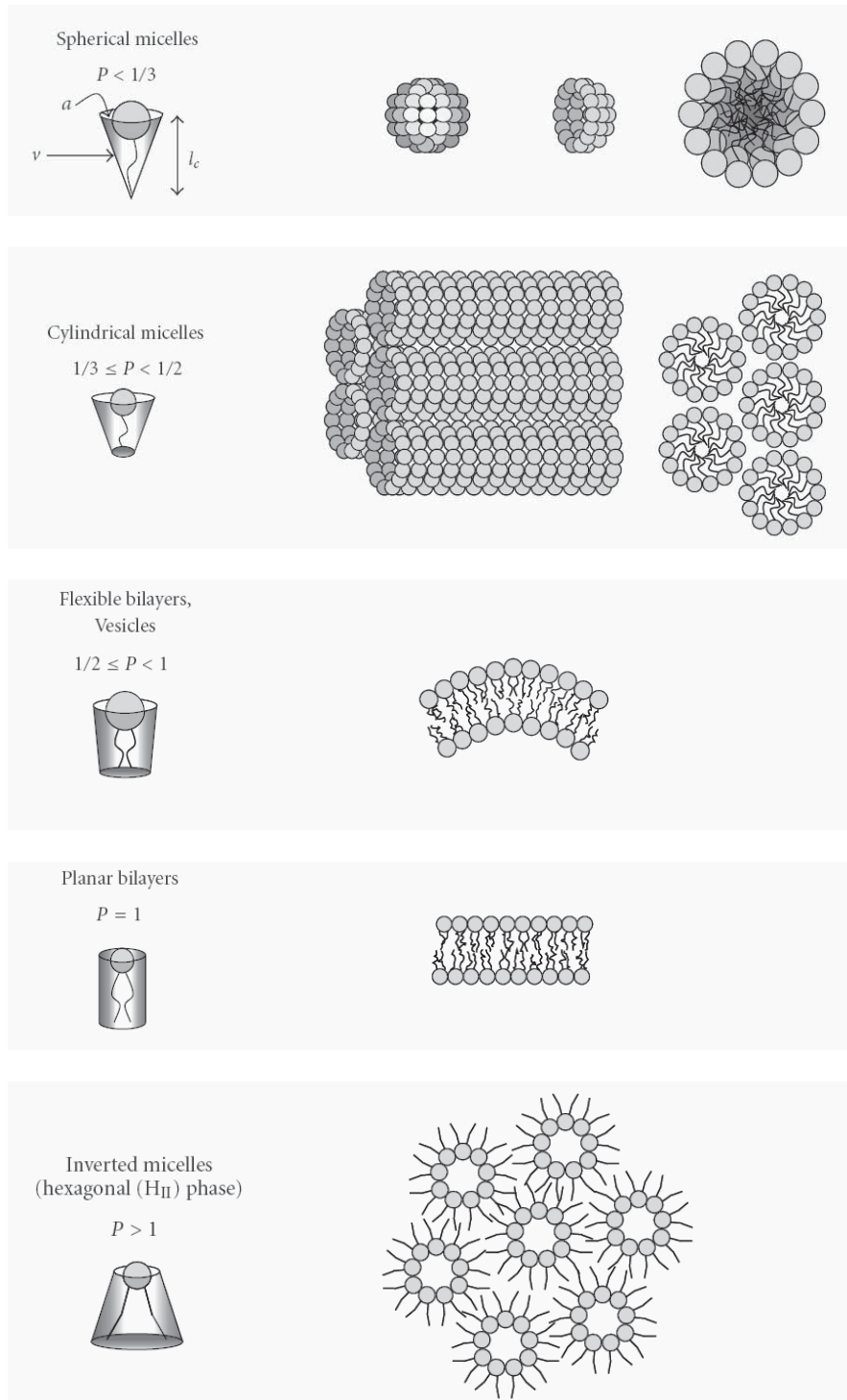
**equation 1.1**

$$P = \frac{v}{a \cdot l_c}$$

where  $v$ ,  $a$ , and  $l_c$  are volume, head group area and length of the amphiphile, respectively.

For surfactants with a broad head group and a short tail,  $P < 1/3$  and spherical micelles are formed, where the water forms the solvent phase. Shifting the packing parameters to higher values (by decreasing  $a_h$  and/or increasing  $l$ ) the surfactant microstructure changes from cylindrical aggregates [3, 4] ( $1/3 < P < 1/2$ ) to bilayers (lamellar phase [5, 6] and vesicles [5, 7-10] ( $P = 1$ ) and finally to the corresponding inverse structures as displayed in chart 1.1.

In the past the static behavior of these morphological structures has been studied intensively due to their central importance for technical and biological applications, which will be discussed in detail later. However, the dynamic properties of amphiphilic systems are only poorly understood and this applies also to the criteria determining the kinetics of structural reorganization processes of such systems.



**chart 1.1** Morphological structures predicted by the packing parameter [11].

Hence, the present work dealt with kinetical aspects in surfactant systems and the influence of parameters, such as charge, steric interactions, and temperature thereof. Three kinetic approaches of fundamental importance for technical applications will be investigated:

The kinetics of the **formation** of amphiphilic structures.

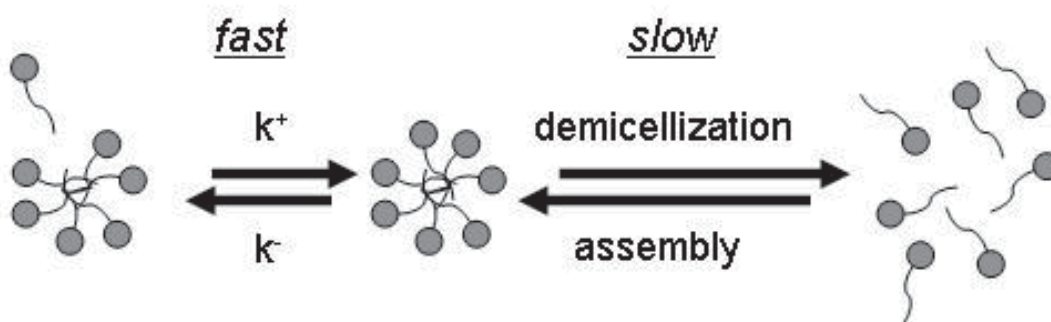
The kinetics of the **exchange** of solubilisate between surfactant aggregates.

On the one hand the morphological transition from micelles/microemulsions to metastable multilamellar vesicles and the formation of thermodynamically stable microemulsions was studied (where the latter is not a process of formation in the common sense because the amphiphilic structure of the starting and the final solution are MEs in both cases; it is therefore more appropriate to speak of equilibration of ME aggregates). The former one is of special technological interest since it has been known for some time now that metastable amphiphilic structures are controlled by the dynamics of their formation [12]. Studying the dynamics of morphological transitions in surfactant systems has become an increasingly active field of colloid research due to the improved experimental time resolution which offers the possibility to gain a more detailed picture of the structural changes involved [13]. Therefore the dynamics of these two formation processes were investigated i.e. by means of time-resolved SAXS measurements. Subsequently specific control of the metastable intermediate structures can be of key importance e.g. in template synthesis and formulations etc.

On the other hand the kinetic of the exchange of oil between ME aggregates was studied in detail. As amphiphiles two technical-grade surfactants were employed. Their structure and properties will be introduced in the following paragraph, where a brief introduction to microemulsions (definition, relevance and application) will be given. The last paragraph of the introduction will deal with the principles of vesicle formation and their importance for technical and biological tasks.

## Microemulsions

Microemulsions are thermodynamically stable dispersions of either water-in-oil (W/O) or oil-in-water (O/W), the stability being the result of the presence of a suitable surfactant [14, 15]. They have been studied intensively due to their enormous potential in many technical applications, e.g. in detergency, ternary oil recovery, formulation of cosmetic, agricultural or pharmaceutical products, and lately the preparation of nanoparticles [16-21]. ME aggregates saturated with hydrophilic (water) or hydrophobic (alkanes) solubilise, consist of small, spherical droplets, exhibiting radii in the range 3 - 30 nm [22]. MEs are thermodynamically stable (they form spontaneously and droplet size is independent of variations in preparation method [23]) which renders them most suitable as reaction medium for enzyme-catalyzed reactions [24, 25], the controlled and selective synthesis [26] and lately the preparation of nanosized particles [19-21].



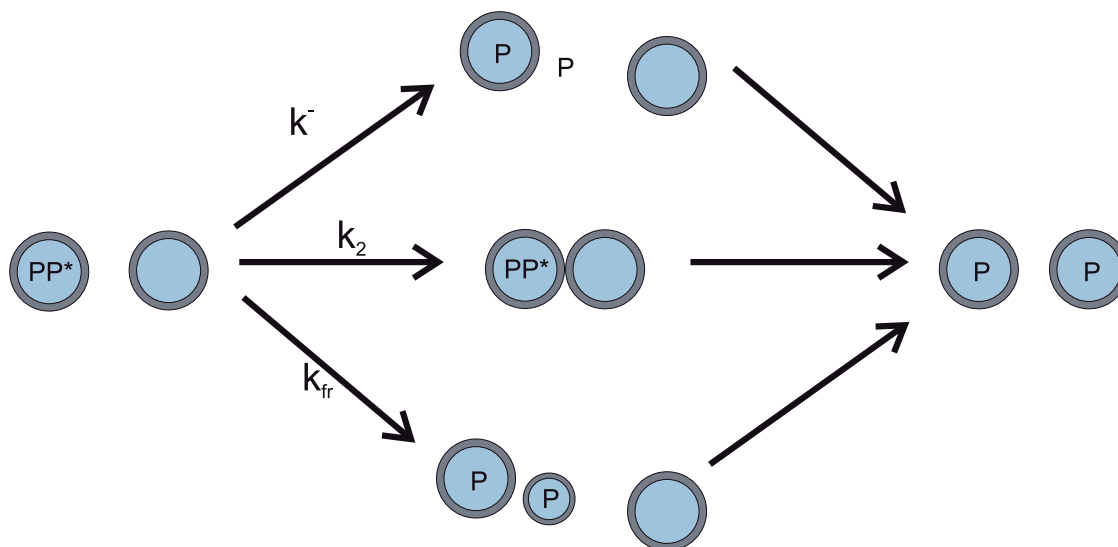
**chart 1.2** Surfactant exchange mechanism and micelle formation and break-down according to Aniansson and Wall [27] where  $k^+$  and  $k^-$  are the exit and entry rates of surfactant molecules (displayed as hydrophilic head group in blue and hydrophobic tail)

Quite a number of publications about micelle dynamics come from chemical relaxation experiments [28-31] that are a powerful means of determining the rates of various relaxation processes. Two well-separated relaxation times have been identified: a rapid relaxation  $\tau_1$ , which requires microseconds and a slower process  $\tau_2$  that occurs on a timescale of seconds or longer. A cartoon describing these two processes is presented chart 1.2. The fast process has been assigned to an association-dissociation process (exchange of individual surfactant molecules between micellar aggregates and the

continuous phase) [27, 32] and values for  $k^+$  and  $k^-$  have been determined, e.g. by performing T-jump experiments for a number of surfactants [33]. The slow process was attributed to the reestablishment of equilibrium through cooperative condensation or dissolution of surfactant monomers (creation and breakdown of entire micelles). However it is difficult, with data from relaxation experiments alone, to establish the mechanism associated with each rate particularly the one of the slow process [34].

When hydrophobic compounds are solubilised into the micellar core, another type of dynamics becomes important: the exchange of solute molecules between micelles/MEs [35]. In contrary to micelles, MEs contain a dispersed state consisting of domain of nanometer dimension. In addition the interfacial tension in a solution of MEs is very small [35]. Both structures represent a thermodynamically stable state of the respective system. Regarding solute exchange between the aggregates three different mechanisms have been proposed:

- \* The first one involves the exit of individual solute or surfactant molecules into the aqueous phase and the entry into another droplet. This exit-reentry mechanism (represented by the relaxation rate  $k^-$ ) becomes dominant when the water solubility of the species is sufficiently high.
- \* During the second mechanism the exchange of solute proceeds via collision of two micelles, followed by their separation. This collision-exchange-separation process, often called fusion-fission mechanism (and represented by the relaxation rate  $k_2$ ), has been suggested as the dominant exchange mechanism in nonionic MEs and nonionic surfactant micelles at high concentration or at elevated temperature [35].
- \* The third possibility for solute exchange involves the fragmentation of a micelle/ME into two sub-aggregates and the subsequent growth into normal micelles/MEs. This fragmentation-growth (represented by the relaxation rate  $k_{fr}$ ) has been suggested as a mechanism to explain rapid exchange between ionic micelles and MEs at high ionic strength [1].



**chart 1.3** Three different mechanisms for solute exchange between microemulsions (black circles refer to the surfactant monolayer; the hydrophobic solute is illustrated as gray-colored interior) where P is the fluorescent probe,  $k^-$  the exit rate for the probe molecule,  $k_2$  the exchange rate for the fusion-fission mechanism and  $k_{fr}$  the exchange rate for the fragmentation-growth mechanism [35]

These three different solute exchange mechanisms are displayed in chart 1.3. The circles refer to the ME (surfactant monolayer: black, solute: gray) and the letter P's refer to both a generic solute and a pyrene derivative that will give excimer fluorescence (see chapter 2.1.2) from aggregates containing two P molecules. The reaction rates  $k^-$ ,  $k_2$  and  $k_{fr}$  correspond to the exchange processes of the exit-reentry, the fusion-fission and the fragmentation-growth mechanism, respectively. In reaction kinetics, in general, the overall rate of a reaction is controlled by the rate of the slowest step. Depending on the number of participating molecules/aggregates etc. the order of reaction can be determined and from that an eligible fit function is selected. For the exit-reentry and the fragmentation-growth mechanism, only one aggregate is involved in the rate determining step. Therefore first-order kinetics is observed as shown in

**equation 1.2**

$$y = y_0 + A \cdot \exp(-k_{obs} \cdot t)$$

where y is the measured variable as function of the time t, for instance the decreasing excimer intensity,  $y_0$  the offset, A the amplitude of the signal and  $k_{obs}$ , the observed

relaxation rate. In many cases a mono-exponential fit function can be employed. The middle path of chart 1.3 will exhibit kinetics second order in ME concentration and can universally be expressed as

**equation 1.3**

$$y = y_0 + \frac{A}{1 + k_{obs} \cdot t}.$$

In the last 30 years only a limited number of authors presented results to understand the mechanism of the slow relaxation process described in chart 1.2. Hence there is a need to attempt to establish parameters of this process in more quantitative terms. As part of such an attempt, we investigate here O/W-microemulsions applying the stopped-flow technique [36, 37] which is a versatile method to study fast kinetics after a rapid mixing process with a time resolution of down to 1 ms, and has been employed in various studies before [38-44]. Details about the mode of operation are given in the experimental section 2.1.1.

Properties of microemulsion systems are to a large degree determined by the elastic properties of the amphiphilic monolayer [45, 46]. Description of MEs in that context is very simple, “*since, because of their low interfacial tensions, the leading term in the free energy should be given by the bending energy, which can be described in terms of two elastic constants, the mean bending modulus  $\kappa$ , and the Gaussian modulus  $\bar{\kappa}$* ” [47]. Here the influence of the composition, especially the cosurfactant concentration, was found to be of particular interest. In the course of this discussion the interrelation between the observed rate constants of the stopped-flow experiments and the macroscopic interfacial tension will be elucidated.



### ***Multilamellar vesicles***

Vesicles are closed amphiphilic bilayers where parts of the solvent is entrapped inside the aggregate and which are often formed in the low-concentration range. In general, vesicles can structurally be subdivided into two main classes. As a first case, they may just be comprised of one single bilayer, as displayed in the chart below and are then referred to as unilamellar vesicles/ ULVs with sizes between 4 – 20 nm for small unilamellar vesicles /SUV and 50 nm - 10  $\mu$ m for large unilamellar vesicles/ LUVs (denotation used in this work see chart 1.4). In addition to the first case there exists also the possibility of multilamellar vesicles/ MLVs (see chart below) where one has various concentric shells of vesicles, thus, these phases are also sometimes called ‘onion phases’ [48]. Vesicles especially from phospholipids (ULVs in this case are often called liposomes) have been investigated widely [10, 49]. They serve as model(s) for membranes and allow therefore studying the basic mechanisms of membrane function. Due to their closed interface they are convenient architectures for encapsulation necessary for pharmaceutical, cosmetic and chemical application.

The kinetic of morphological transitions in amphiphilic systems is important for the understanding of many applications but so far no comprehensive study has been done. The formation of vesicles is not a thermodynamically controlled process. In many cases the final vesicle phase is not in thermodynamic equilibrium but instead long-lived metastable structures are observed. Accordingly the properties of such systems depend strongly in the preparation of the sample and are therefore controlled by the kinetics of their formation process. The knowledge of the dynamics during the formation of the vesicles is crucial to influence the properties of the final state which is especially important in industrial applications.

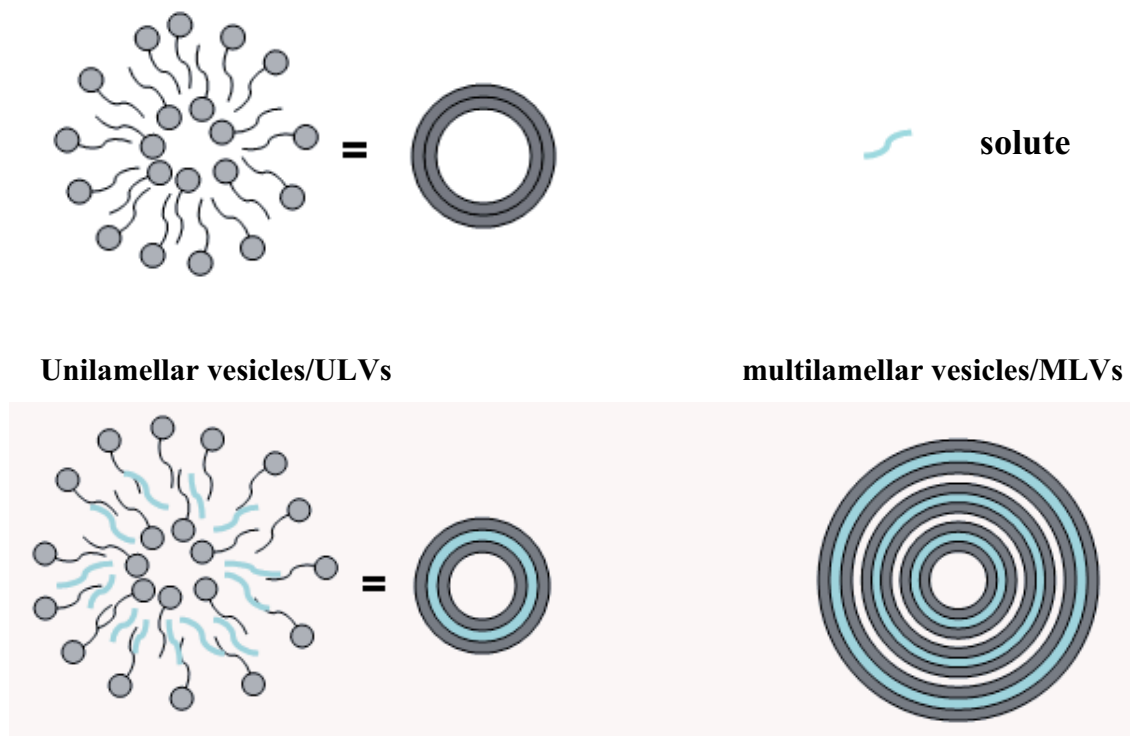
As already mentioned above, the elastic properties of amphiphilic monolayers and bilayers, as they are typically formed in self-assembling structures, are an important factor in understanding their properties [47] and can be described by a spontaneous curvature  $c_0$  and two elastic constants  $\kappa$  and  $\bar{\kappa}$  associated with the mean curvature and the Gaussian curvature, respectively. These parameters are very important in the determination of the structure and phase sequences in surfactant systems, i.e. droplets or sponge-like structures and are interrelated in the harmonic approximation of the

continuum bending free energy,  $F_b$ , of a monolayer or bilayer established by Helfrich in 1973 [50]:

**equation 1.4**

$$F_b = \int dA \left[ \left( \frac{\kappa}{2} \right) \cdot (c_1 + c_2 - 2c_0)^2 + \bar{\kappa} \cdot c_1 \cdot c_2 \right]$$

where  $c_1$  and  $c_2$  are the principal curvatures of the amphiphilic film,  $\kappa$  and  $\bar{\kappa}$  are the mean and Gaussian bending moduli and  $A$  is the surface area. With this approximation one can calculate the energy of the different topologies of a surfactant film and thus determine the most stable structures. The expression for  $F_b$  in equation 1.4 is essentially an expansion of the free energy for small curvatures and is correct in the limit of radii of curvatures that are large compared with the thickness of the film [51].



**chart 1.4** Illustration of unilamellar and multilamellar vesicles

Depending on the spontaneous curvature of the surfactant monolayer, O/W-MEs are stable for positive  $c_0$  and W/O-MEs for negative values. For the balanced state (phase inversion temperature) of the monolayer, breaking on the emulsion is to be expected [52]. In many droplet microemulsions, the magnitude of  $c_0$  also determines the maximum droplet size (maximum solubilization power [53]). Values for  $\kappa$  are always positive. The second term of equation 1.4 takes into account the fact that the system can change its topology:  $\bar{\kappa}$  is negative for lamellar or spherical, whereas positive favours saddle-splay structures as in bicontinuous cubic or sponge phases. Usually  $F_b$  is negligible compared to the interfacial tension contribution. However, in ME systems, the interfacial tension is small or even zero and the bending energy becomes a very important term [53].

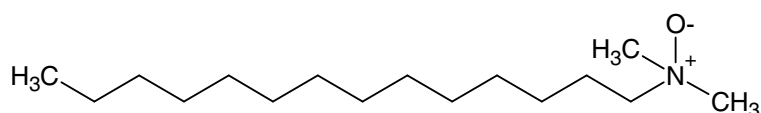
By means of e.g. neutron spin echo experiments, it is possible to determine values of  $\kappa$  exclusively. However, a combination of data sets of complementary methods is necessary to calculate  $\bar{\kappa}$ . Therefore, it has been found that the sum of the mean and Gaussian bending modulus for liquid films,  $2\kappa + \bar{\kappa}$  can be used to describe the elasticity of an amphiphilic film. Values for  $2\kappa + \bar{\kappa}$  can be derived relatively easily e.g. from interfacial tension or SANS measurements. In 1999, Safran has given a nice overview of the field of curvature elasticity that discusses fundamentals, the effects of fluctuations and inhomogenities and gives a brief review of experimental characterizations on surfactant system [51]. A special task of this work was the comparison of the experimentally obtained values of the sum  $2\kappa + \bar{\kappa}$  of the bending constants with the generated phase diagrams in a ternary surfactant system which will be discussed in detail in chapter 6.

### ***Investigated surfactant systems***

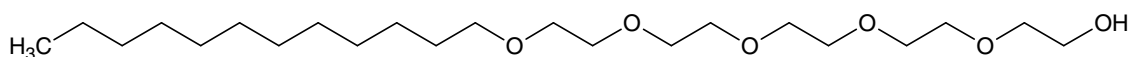
As amphiphiles, the zwitterionic semipolar surfactant tetradecyldimethylamine oxide (TDMAO) (see chart 1.5) was employed throughout this work to study both kinetic approaches, (a) and (b). The class of alkylamine oxides, with their mesoionic character, shows a behavior between those of typical nonionic and cationic surfactants of identical chain length [54-56]. At ambient temperature TDMAO can serve as a model system for nonionic surfactants with a reasonable solubilisation capacity as it has been reported for the ternary system TDMAO/decane/water [57].

For the formation of microemulsions very often the presence of a cosurfactant is required that lowers the interfacial tension between the oil phase and the water phase which for a pure surfactant often is too high [58, 59]. Cosurfactants like the medium-chain hexanol are amphiphilic compounds of low molecular weight. They are not able to build micellar structures by themselves but, due to their molecular structure, they increase the packing parameter of the surfactant interface, thereby increasing the solubility for hydrophobic compounds significantly.

**TDMAO**



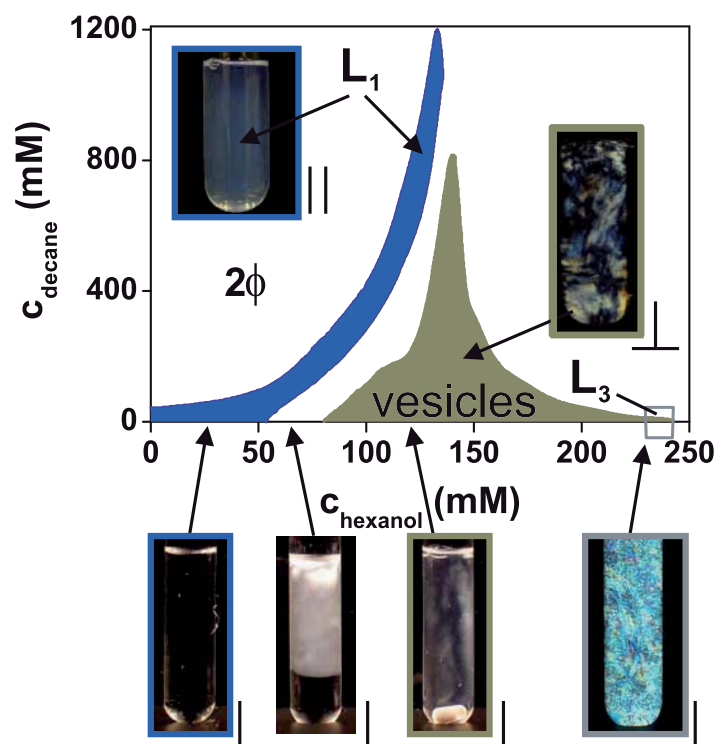
**C<sub>12</sub>E<sub>5</sub>**



**chart 1.5** Structures of both surfactants employed in this work (tetradecyldimethylamine oxide/TDMAO) and penta(ethylene oxide) monododecyl ether/C<sub>12</sub>E<sub>5</sub>)

In the quaternary system 100 mM TDMAO/hexanol/decane/water described previously [60] the addition of 1.3 molecules of hexanol per surfactant molecule leads to a reduction of the interfacial tension by a factor of  $\sim 100$ , and causes an increase of the solubilisation capacity from 0.35 to 12 molecules of decane per surfactant molecule compared to the ternary system without cosurfactant. In the phase diagram of the quaternary system at constant surfactant concentration is displayed in figure 1.1, where one observes a very extend range of an oil-in-water (O/W) microemulsion (the so-called L<sub>1</sub>-phase; blue area) with very different droplet sizes and droplet concentrations, at a given surfactant concentration. In the phase diagram in figure 1.1, beyond the range of the L<sub>1</sub>-phase, without the addition of decane and separated by a two-phase region, the isotropic L<sub>α</sub>-phase is found (green area). At low hexanol concentration, vesicles (L<sub>α1</sub>-phase)

exhibiting flow-birefringence are present (Pictures of the ternary and quaternary system taken under normal conditions ( $\parallel$ ) and crossed polarizers ( $\perp$ ) are presented in figure 1.1). When the hexanol concentration is increased further, this phase will become increasingly birefringent and is now composed of a mixture of vesicles with lamellar chunks ( $L_{\alpha h}$ -phase). Finally at still higher hexanol concentrations a  $L_3$ -phase (sponge phase) is observed. Addition of decane leads to the formation of a liquid crystalline lamellar phase that swells by taking up the oil into the lamellar sheets [61].



**figure 1.1** Phase diagram of the system 100 mM TDMAO/1-hexanol/decane/water [61] at 25 °C.  $L_1$ , isotropic O/W microemulsion (blue); vesicles, partially birefringent phase (green);  $L_3$ , sponge phase;  $2\Phi$ , two-phase region. Picture of the ternary and quaternary system taken under normal conditions ( $\parallel$ ) and crossed polarizers ( $\perp$ ). Vesicles in the ternary system (without decane) show flow birefringence

The above mentioned  $L_1$ -phase contains ME droplets of spherical shape with a maximum size and perfect sphericity at the upper solubilisation limit (emulsification boundary). This renders this system interesting as it allows following equilibration of microemulsions after mixing two differently sized microemulsions. Therefore

stopped-flow measurements with complementary detection methods (turbidity, fluorescence and SAXS) were performed to monitor the equilibration process in detail. Alternatively one can also follow the exchange of solubilisate in identically composed and sized microemulsions by appropriate methods. For that task stopped-flow fluorescence measurements were conducted. The first approach is in general experimentally more easily done but rather difficult to analyze while the second is experimentally more demanding but simpler to analyze.

However, in order to study the influences of different participations to the experimentally achieved exchange rates, as a pre-condition, the surfactant system at hand should be dilutable at least by a factor of 10. This is not possible in the quaternary system with the amine oxide, whereas it is easily achieved for nonionic surfactants of the poly(ethylene oxide) monoalkyl ether type. Here, ternary MEs with penta(ethylene oxide) monododecyl ether,  $C_{12}E_5$  (where  $i$  and  $j$  denote the length of the alkyl chain and the ethoxy unit respectively) (see chart 1.5) as surfactant proved to be easier for the investigation of solute exchange. The micellar solution was loaded with octane, decane and dodecane and oil-swollen spherical ME at the solubilisation limit were achieved which is a prerequisite to gain reliable information during kinetic measurements.

In both the quaternary and the ternary system, the influences of temperature and the addition of additives, like ionic surfactants and polymers, were tested. This then allows learning how electrostatic interactions and thickness of the amphiphilic film affect these processes. An interesting class of adsorbing polymers consists of the so-called hydrophobically modified (HM) water-soluble polymers, with a water-soluble polymer backbone and covalently bounded hydrophobic side chains [62]. They were found to have considerable impact on the exchange kinetics and a quantitative analysis will be given here.

Concerning the spontaneous formation of multilamellar vesicles, in this work the phase diagrams of four ternary systems with TDMAO as dispersant are presented. As solute, esters of different alkyl chain length were incorporated and the impact of the decreasing polarity on the phase behavior was studied. Due to the symmetric vesicle phase, the ternary system TDMAO/enanthic methyl ester (EME)/water [63] at a constant surfactant concentration of 200 mM, i.e.  $\sim 5$  wt% was employed, and the structural transition from a

mixture of the micellar and microemulsion phase to form a vesicle phase was studied. Furthermore the question of having charged amphiphilic mono- and bilayers present during the process of vesicle formation (as introduced by admixing an ionic surfactant) was addressed. The quantitative results were studied i.e. by stopped-flow measurements with simultaneous detection in turbidity and conductivity mode are presented.

**This thesis is structured as follows:**

In chapter 3 a comprehensive study will be presented on the exchange dynamics between MEs of a ternary system with  $C_{12}E_5$  as surfactant. In addition quantitative information about solubilisate exchange and the equilibration of MEs in the quaternary system TDMAO/1-hexanol/decane/water were obtained and presented in chapter 4.

In the second part of this work the influence of cosurfactants of medium polarity (esters) on the phase behavior of TDMAO in water were investigated. These systems proved most suitable to study the kinetics of morphological transitions, i.e. in this case the formation of multilamellar vesicles, in mesoscopically structured amphiphilic systems. This process has been investigated for various starting conditions and as a function of the charging of the amphiphilic system with advanced time-resolved methods, e.g. stopped-flow DLS and SAXS.